Benthic estuarine communities in Brazil: moving forward to long term studies to assess climate change impacts

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Abstract

Estuaries are unique coastal ecosystems that sustain and provide essential ecological services for mankind. Estuarine ecosystems include a variety of habitats with their own sediment-fauna dynamics, all of them globally undergoing alteration or threatened by human activities. Mangrove forests, saltmarshes, tidal flats and other confined estuarine systems are under increasing stress due to human activities leading to habitat and species loss. Combined changes in estuarine hydromorphology and in climate pose severe threats to estuarine ecosystems on a global scale. The ReBentos network is the first integrated attempt in Brazil to monitor estuarine changes in the long term to detect and assess the effects of global warming. This paper is an initial effort of ReBentos to review current knowledge on benthic estuarine ecology in Brazil. We herein present and synthesize all published work on Brazilian estuaries that has focused on the description of benthic communities and related ecological processes. We then use current data on Brazilian estuaries and present recommendations for future studies to address climate change effects, suggesting trends for possible future research and stressing the need for long-term datasets and international partnerships.

Descriptors: Estuaries, Benthic ecology, Climate change, Brazil, Impacts

Resumo

Estuários são ecossistemas costeiros que sustentam uma ampla variedade de serviços ambientais para a humanidade. Estuários abrigam muitos ambientes bentônicos com características específicas e seriamente ameaçados globalmente. Manguezais, marismas e planícies de maré são amplamente impactados por poluentes domésticos e industriais, por atividades comerciais que levam à perda de *habitat* e pela sobrepesca. Os diversos impactos locais, associados a mudanças regionais e globais na hidromorfologia estuarina e potenciais efeitos de mudanças climáticas, colocam sérias ameaças a ecossistemas estuarinos. A rede Bentos foi criada para estudar o efeito de mudanças no clima em ecossistemas bentônicos costeiros brasileiros. Este trabalho faz parte dos esforços iniciais do Grupo de Trabalho Estuários em rever o conhecimento sobre comunidades bentônicas estuarinas no Brasil. Aqui apresentamos uma breve revisão crítica sobre os trabalhos realizados objetivando o estudo, em nível de comunidades, do bentos estuarino e processos ecológicos associados. A partir do cenário atual, realizamos recomendações de estudo para responder questões científicas sobre efeitos de mudanças climáticas em comunidades bentônicas estuarinas, e enfatizamos a necessidade de bases de dados contínuas e de longa duração e o estabelecimento de parcerias internacionais com foco específico nos estuários brasileiros.

Descritores: Estuários, Ecologia bêntica, Mudança climática, Brasil, Impactos

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INTRODUCTION

Estuarine benthic ecosystems are heterogeneous systems that provide highly diverse habitats and their biological assemblages are frequently used as indicators of natural and anthropogenic changes. The spatial and temporal variability of estuarine populations and communities are largely conditioned by climate, run-off regimes and oceanic dynamics, through changes in nutrients, primary production and sediments (MALLIN et al., 1993; HEIP et al., 1995). Thus estuarine fauna must be highly adapted to deterministic and stochastic environmental changes (ELLIOTT and QUINTINO, 2007) which may occur on a local, regional or global scale. Local and regional changes may be linked to the relative dominance of riverine, wave or tidal processes directly affecting habitat diversity and spatial and temporal gradients in sediments and organic matter.

Brazil has a long coastline with over one hundred estuaries from the tropical equator in the North to due to regions in the South. Brazilian estuaries differ widely in their tidal regimes (e.g. from macrotidal on the northern to microtidal on the southeastern and southern coasts), input of run-off discharges (i.e., higher average rainfall in the northern and southern regions) and wave action. Geomorphological differences are also main causes of dissimilarities among Brazilian estuaries (DOMINGUEZ, 2006). Estuaries dominated by riverine inputs are more frequent in the N and NE and within bays, and drowned estuaries and lagoons are more common in the SE and S. Macroscale changes associated with large-scale environmental differences in Brazilian estuaries may be due to atmospheric, oceanographic and climate variability, as well as to local or regional human activities. Global climate dynamics could, therefore, act directly upon local estuarine benthic populations or promote cross-scale interactions influencing species responses on both local and regional scales.

Estuaries have been intensely modified over recent decades by human activities. Sewage outfalls and eutrophication, habitat loss, overfishing and several hydrodynamic changes have produced marked impacts worldwide (NORKKO et al., 2002; SCAVIA et al., 2002). Brazilian estuaries are no exception and several studies have reported multiple human impacts near large urban areas (SANTI and TAVARES, 2009; SOARES-GOMES et al., 2012; KRULL et al., 2014). It is widely accepted that potential effects of climate change will further impact estuarine communities by changes in average temperature, in yearly rainfall and in mean sea level (ATTRILL and POWER, 2000; NAJJAR et al., 2000; GILLANDERS and KINGSFORD, 2002). However, it is still extremely difficult to predict the intensity and scale of these changes and the response of biological communities and changes in ecosystem functioning. Temperature and rainfall anomalies, as well as sea level rise, have been commonly reported across the globe and these effects may have substantial impacts on estuarine ecosystems over both the short- and long-term (ALONGI, 2008; DAY et al., 2008; CONDIE et al., 2012; TURRA et al., 2013; GARCÍA-RODRIGUEZ ET AL., 2014). For example, if regional and local rainfall anomalies and sea level changes alter the salt balance of an estuary, it might cause changes in species distribution and productivity (THURMAN et al., 2010; CONDIE et al., 2012). Higher temperatures could also affect the metabolism, growth and reproduction of estuarine biota, which combined with local eutrophication may lead to oxygen depletion and mass mortality of organisms (BISHOP et al., 2006). It is expected that the intensity of impacts and ecological effects of climate change on estuaries will be site-specific. However, long-term changes in climate may also alter estuarine communities and ecosystem resilience on larger scales that are relevant to ecosystem management and function (DOLBETH et al., 2011; ELLIOTT and WHITFIELD, 2011; MCLEOD et al., 2011).

Projected changes in global climate are the greatest current threat to ecological function and the associated socio-economic services provided to mankind (ANTLE et al., 2001; DONEY et al., 2012; TURRA et al., 2013). As such, the major challenge to modern ecology is to understand and to predict how climate change will translate into ecological impacts and affect human well-being. To scientifically assess changes in estuarine ecosystems and promote their long-term conservation and management, we have created "The Monitoring Network for Coastal Benthic Habitats" (ReBentos - Working group on Estuaries), an integrated effort on the part of researchers and institutions along Brazil's 8,000 km of coast line. ReBentos's main goals are to establish long-term observations of benthic estuarine communities and other coastal ecosystems, through sound scientific practices to detect and assess the effects of climate change. The ReBentos Estuaries working group's assignment is to develop studies using the estuarine benthic fauna as a biological model for climate change assessment. Benthic ecosystems are particularly useful to understand how estuaries will be affected by climate change because they are the key to many biogeochemical and ecological processes at the sediment water interface (SMITH et al., 2000; KRISTENSEN et al., 2008). Benthic communities are also overwhelmingly used as indicators of the biotic quality of estuarine ecosystems, and thus the ReBentos project's efforts qualify it for inclusion among several international programs with similar goals (e.g. Climate Ready Estuaries - EPA/USA; Marbef network program - EU).

In order to design and propose a long-term monitoring program, we have carried out an exhaustive synthesis of published work on the benthic communities of estuarine ecosystems in Brazil and have assessed their vulnerability to past and current changes in temperature and rainfall (BERNARDINO et al., 2015a). These theoretical predictions may be useful to address site-specific vulnerabilities in several Brazilian estuaries to projected climate change and result in mitigation and adaptation on a regional scale. The ReBentos network has proposed several protocols to standardize historical time series data acquisition on benthic estuarine ecosystems across Brazil. In order to suggest best scientific practices for long-term monitoring of benthic ecosystems, this paper: i) critically reviews the published work on estuarine benthic invertebrates along the Brazilian coast in respect to their usefulness as baselines for climate change studies; ii) suggests a long-term sampling protocol using benthic communities as models for climate-related impacts in estuaries, and iii) compares the ReBentos Estuaries protocol with current international strategies with similar objectives.

MATERIAL AND METHODS

A review of all work published in peer-reviewed and indexed journals up to and including 2012 was made by means of the Web of Science®, SCOPUS and Google Scholar. Benthic compartments, including meiofauna, macrofauna and megafauna, were selected after satisfying the basic criterion of focusing on community ecology. Taxonomic surveys and other specific work on benthic fauna were not included in this review but can be found elsewhere (LANA et al., 1996). Selected papers were classified according to 1) region (N, NE, SE and S), 2) habitat (mangrove forest, saltmarsh, unvegetated sediments), 3) tidal position (subtidal or intertidal), and 4) sampling interval (months to years and number of sampling events during the study).

RESULTS

A total of 50 published papers on the benthic estuarine communities of 48 different estuaries were found (Table 1). These papers cover roughly three decades of study - from 1986 to 2012, with sampling efforts concentrated in the more developed areas of southern and southeastern Brazil (ca. 75% of published papers; Figure 1). Despite the greater number of studies of estuaries from the southeastern and southern regions, most published works were concentrated on a few sites (Figure 1). The Northeastern region had a higher number of estuaries studied than did the Northern region, although both had generally a lower number of studies published (Figure 1). The sampling effort was greater in a few estuaries in the S and SE. For example, the estuarine systems of Guanabara Bay (RJ), Cananéia (SP), Paranaguá Bay (PR) and Patos Lagoon (RS) were intensely studied in respect to their benthic fauna and ecosystem dynamics (Table 1). On the other hand, most estuaries were investigated in respect to their community description on local to regional scales and only at a few sites were studies of a more general nature (e.g. community succession, pollution effects, trophic interactions) or where in situ experimentation been carried out included.

Benthic macrofaunal communities in subtidal channels and on intertidal flats were the most studied estuarine habitats along the Brazilian coast (Figure 1). Macrofaunal communities in saltmarshes (*Spartina*) were mainly studied on the northern and southern coasts in Pará, Santa Catarina, Paraná and Rio Grande do Sul (Figure 1). Megafaunal communities were mostly studied in mangrove forests and on hard substrates, with some efforts made in subtidal estuarine channels in some areas. On the eastern and southeastern coasts, macrofaunal and megafaunal communities were investigated in the polluted urban areas of the Pernambuco coast, Vitoria (ES), Guanabara (RJ) and Santos (SP). Benthic communities in mangrove forests and, saltmarshes and tidal flats were also studied in a few preserved areas of Rio de Janeiro and São Paulo in the southeast (Table 1). Significant sampling efforts on intertidal communities of unvegetated flats, saltmarshes and mangrove sediments were carried out in estuaries on the southern coast. In general, epifaunal communities in mangrove forests and *Spartina* marshes and on rocky substrates at specific sites were little studied.

Most benthic estuarine studies in Brazil have focused either on the description of patterns of community

Table 1. Summary of selected published papers on the benthic ecology of Brazilian estuaries from 1986 to 2012.

Area	State	Estuarine Habitats	Site	Depth	Sampling interval	Benthic fauna	Reference
Pará, Northern Brazil	PA	Tidal flat	Caeté estuary	Intertidal	2 days	Macrofauna	ROSA FILHO et al., 2006
	PA	Saltmarsh (*Spartina*)	Eight estuaries along Pará coast	Intertidal	1 year, 4 sampling events	Macrofauna	BRAGA et al., 2011
	PA	Mangrove	Caeté estuary		1 sampling event	Megafauna	KOCH and WOLFF, 2002
Pernambuco, Northeast Brazil	PE	Mangrove	Itamaracá Island	Intertidal	Not determined	Megafauna	COELHO DOS SANTOS and COELHO, 2001
	PE	Tidal flat	Itamaracá Island	Intertidal (control area)	up to 153 days (experimental)	Macrofauna	BOTTER-CARVALHO et al., 2011
	PE	Mangrove	Suape Bay		1 sampling event	Megafauna	FARRAPEIRA et al., 2009
	PE	Channel	Fourteen estuaries of PE State	Subtidal	1 sampling event	Macrofauna	VALENÇA and SANTOS, 2012
Bahia, Northeast Brazil	BA	Mangrove and Channel	Cachoeira river, Ilhéus	Intertidal and subtidal	5 years - qualitative only	Megafauna	ALMEIDA et al., 2006
	BA	Channel	Paraguaçu river		6 months, 2 sampling events	Macrofauna	BARROS et al., 2008
	BA	Channel	Paraguaçu, Subaé and Jaguaripe rivers		6 months, 2 sampling events	Macrofauna	MAGALHAES and BARROS, 2011
	BA	Channel	Camamu Bay	Subtidal	1 sampling event	Macrofauna	PAIXÃO et al., 2011
	BA	Channel	Cachoeira river, Ilhéus	Subtidal	1 year, monthly	Macrofauna	OURIVES et al., 2011
	BA	Channel	Paraguaçu, Subaé and Jaguaripe rivers		6 months, 2 sampling events	Macrofauna	BARROS et al., 2012
Espírito Santo, Southeast Brazil	ES	Channel	Vitoria Bay	Intertidal and subtidal	1 year, every 3 months	Macrofauna	NALESSO et al., 2005
	ES	Rocky	Vitória Bay		3 months, 6 sampling events	Megafauna and macrofauna	ZALMON et al., 2011
Rio de Janeiro. Southeast Brazil	RJ	Mangrove	Sepetiba Bay	Intertidal	1 year, 6 sampling events	Megafauna	OSHIRO et al., 1998
	RJ	Channel	Guanabara Bay	Subtidal	3 years, 4 sampling events	Megafauna	LAVRADO et al., 2000
	RJ	Channel	Guanabara Bay	Subtidal	1 year, 2 sampling events	Macrofauna	SOARES-GOMES et al., 2012

Continued Table 1.

	RJ	Channel	Guanabara Bay	Subtidal	1 year, 2 sampling events	Macrofauna	SANTI and TAVARES, 2009
	RJ	Tidal flats	Guanabara Bay	Intertidal	1 year, 3 sampling events	Macrofauna	OMENA et al., 2012
	RJ	Rocky	Guanabara Bay	Intertidal	2 years, 8 sampling events	Megafauna	JUNQUEIRA et al., 2000
	RJ	Channel	Saquarema--Jaconé	Subtidal	1 year, 4 sampling events	Macrofauna	MENDES and SOARES-GOMES, 2011
São Paulo, Southeast Brazil	SP	Mangrove	Seven mangrove areas in the state	Intertidal	1 year, monthly	Megafauna	COLPO et al., 2011
	SP	Saltmarsh	Cananéia estuary	Intertidal	1 year, monthly	Macrofauna	TARARAM and WAKABARA, 1987
	SP	Channel	Cananéia estuary	Subtidal	1 sampling event	Macrofauna	TOMMASI, 1970
	SP	Tidal flats	Cananéia estuary	Intertidal	1 year, 5 sampling events	Macrofauna	VAROLI, 1990
	SP	Tidal flats	Santos estuarine system	Intertidal	1 year, 4 sampling events	Macrofauna	CORBISIER, 1991
	SP	Saltmarsh	Cananéia estuary	Intertidal	1 year, 8 sampling events	Macrofauna	ATTOLINI et al., 1997
Paraná, South Brazil	PR	Tidal flats	Guaratuba Bay	Intertidal	1 year, monthly	Megafauna	MASUNARI, 2006
	PR	Channel	Paranaguá Bay	Subtidal	1 sampling event	Macrofauna	LANA, 1986
	PR	Saltmarsh (*Spartina alterniflora*)	Paranaguá Bay	Intertidal	14 months, monthly sampling	Macrofauna	LANA and GUISS, 1991
	PR	Tidal flats	Paranaguá Bay	Intertidal	up to 18 days (experimental)	Macrofauna	NETTO and LANA, 1994
	PR	Tidal flats	Paranaguá Bay	Intertidal	6 months, 2 sampling events	Macrofauna	NETTO and LANA, 1997
	PR	Tidal flats, Salt marshes and Mangrove	Paranaguá Bay	Intertidal	1 sampling event	Macrofauna	LANA et al., 1997
	PR	*Spartina salt* marsh	Paranaguá Bay	Intertidal	6 months, 2 sampling events	Macrofauna	NETTO and LANA, 1999
	PR	Tidal flats and Channel	Baía de Guaratuba	Subtidal	1 sampling event	Macrofauna	BLANKENSTEYN and MOURA, 2002
	PR	Tidal flats	Paranaguá Bay	Intertidal	64 days (exeprimental)	Macrofauna	FARACO and LANA, 2003

Continued Table 1.

	PR	Tidal flats	Paranaguá Bay	Intertidal	95 days (experimental)	Macrofauna	FARACO and LANA, 2004
	PR	Salt marshes	Paranaguá Bay	Intertidal	120 days (experimental)	Macrofauna	PAGLIOSA and LANA, 2005
Santa Catatrina, South Brazil	SC	Mangrove	Estuary of Ratones River	Intertidal	1 sampling event	Meiofauna and Macrofauna	NETTO and GALLUCCI, 2003
	SC	Channel	Laguna Estuarine System	Subtidal	2 sampling events	Macrofauna	FONSECA and NETTO, 2006
	SC	Mangrove and Channel	Bay of Santa Catarina island	Subtidal	1 sampling event	Macrofauna	PAGLIOSA and BARBOSA, 2006
	SC	Channel	Laguna Estuarine System	Subtidal	1 year, 12 sampling events	Macrofauna	MEURER and NETTO, 2007
	SC	Mangrove	Santa Catarina island	Intertidal	1 year, 13 sampling events	Megafauna	BRANCO, 1990
Rio Grande do Sul, South Brazil	RS	Tidal flats	Patos Lagoon	Intertidal	1 sampling event	Macrofauna	ROSA and BEMVENUTI, 2004
	RS	Tidal flats	Patos Lagoon	Intertidal	6 months, 4 sampling events	Macrofauna	BEMVENUTI et al., 2003
	RS	Channel	Patos Lagoon	Subtidal	63 days (experimental)	Macrofauna	SOARES et al., 2004
	RS	Channel	Patos Lagoon	Subtidal	1 year, 4 sampling events	Macrofauna	BEMVENUTI et al., 2005
	RS	Tidal flats	Patos Lagoon	Intertidal	1 year, 12 sampling events	Macrofauna	COLLING et al., 2007
	RS	Saltmarsh (*Ruppia maritima*)	Patos Lagoon	Subtidal	2 sampling events	Macrofauna	ROSA and BE-MVENUTI, 2007

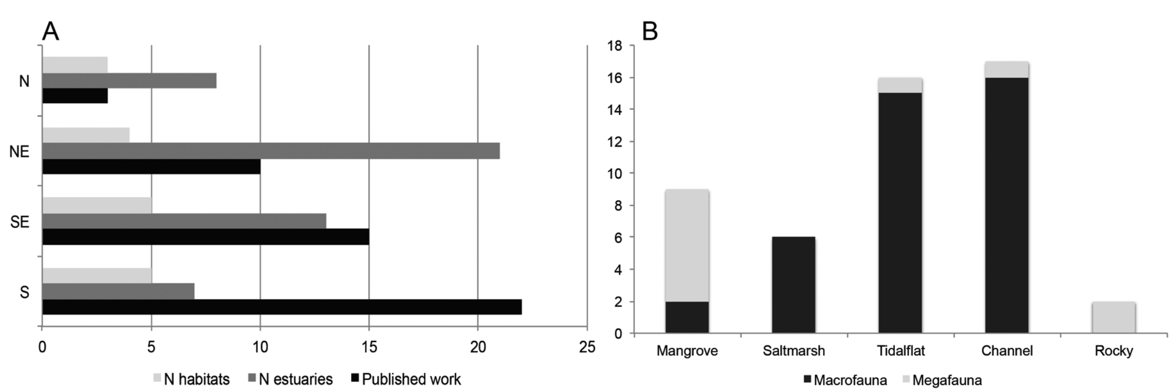

Figure 1. A. Distribution of selected published studies on benthic estuarine communities, number of estuaries and habitats within each region along the Brazilian coast from 1986 to 2012. B. Number of studies per habitat and proportion of studies addressing macrofaunal or megafaunal communities.

distribution and structure, or their relationship with environmental drivers and pollution effects. Descriptive studies overwhelmingly dominate those of all estuarine habitats and account for 60% of all published papers. Changes in community structure occur due to spatial changes of salinity, sediment composition and hydrodynamics at both tropical and subtropical estuaries (LANA et al., 1997; FONSECA and NETTO, 2006; COLLING et al., 2007; BARROS et al., 2008). The influence of habitat on benthic communities is also closely related to the vegetation and its organic detritus in addition to changes in the structure and distribution of communities between rainy and dry seasons (NETTO and LANA, 1999; PAGLIOSA and LANA, 2000; COLLING et al., 2007; MEURER and NETTO, 2007). Overall, there is a local increase in benthic species richness at vegetated sediments, most likely due the increased habitat complexity (NETTO and LANA, 1999).

The spatial and temporal patterns of benthic communities were investigated through a few (n = 1 to 4) sampling events during 6-month periods. The abiotic factors investigated included salinity, sediment properties (i.e. grain size and organic matter), presence or absence of vegetation and natural or anthropogenic disturbance (i.e. physical disturbance of sediment and pollution. Table 1). Seasonal dynamics of benthic fauna, over up to a year, were less often investigated (38% of published papers). Unvegetated flats and channels were commonly studied through monthly sampling (sometimes less frequently) for periods of a year. The benthic fauna of vegetated mangrove forests and salt marsh sediments were rarely sampled for periods longer than 6 months (Table 1). Long-term studies, which includes those on inter-annual temporal scales of > 2 years, are clearly missing for all benthic estuarine habitats except for a few exceptions across Brazil (n = 4). Information on seasonal and interannual variability of benthic estuarine communities is spatially highly limited. For example, we have found a 4-year qualitative survey on the carcinofauna of mangrove forests and estuarine sediments in NE Brazil (ALMEIDA et al., 2006). Another 3-year sampling with only 4 trawling campaigns studied the benthic megafauna within Guanabara Bay, which was also studied in respect to its rocky shore communities over a 2-year period (JUNQUEIRA et al., 2000; LAVRADO et al., 2000). The longest time series study of benthic macrofauna was carried out on a saltmarsh in Paranaguá Bay (LANA and GUISS, 1991), which was sampled monthly for 14 months.

DISCUSSION

Moving from community structure to ecological processes

There is an urgent need to increase the number of field surveys in poorly studied regions. Past and current descriptive efforts are clearly important to describe and discriminate varying estuarine patterns along the Brazilian coast. As these estuaries are fundamentally distinct in respect to their geomorphology and oceanographic conditions and are under various climatic regimes, additional investigations will certainly lead to a better recognition of associated benthic communities and site-specific responses (GILLANDERS and KINGSFORD, 2002; SOARES et al., 2014). Indeed, there is strong evidence for local and regional heterogeneity of estuarine benthic communities among habitats (NETTO and LANA, 1997; EDGAR and BARRETT, 2002; BARROS et al., 2012). Such heterogeneity may lead to variable community-environment responses of benthic fauna at different estuaries. In any case, these surveys would clearly benefit from standard protocols for community assessment and data analysis, allowing the identification of large scale patterns and potentially leading to more accurate models.

However, it is also necessary to move research questions from the basic descriptions of community structure to the understanding of the ecological processes that regulate benthic dynamics in Brazilian estuaries. The investigation of ecological processes in benthic communities has advanced through intensive sampling and field manipulative experiments in SE and S Brazil, with greater effort directed to unvegetated flats and saltmarshes. As has been revealed for temperate and tropical estuaries in the Northern hemisphere, significant differences in community structure, succession and trophic processes occur between vegetated and unvegetated sediments in subtropical estuaries (LANA and GUISS, 1992; NETTO and LANA, 1999). Manipulative and mensurative experiments also revealed the responses of benthic communities to nutrient loading and pollution effects, which greatly improved our understanding of mechanisms of community resilience and succession after disturbance (FARACO and LANA, 2003; MENDES and SOARES-GOMES, 2011; GERN and LANA, 2013; SOUZA et al., 2013). Recognising these patterns on local and regional scales allows for better predictive models of benthic community responses to habitat modification, species invasion and subsequent changes in sediment biogeochemistry (NEIRA et al., 2005; DEMOPOULOS et al., 2007; CANNICCI et al., 2008; DEMOPOULOS and SMITH, 2010; SWEETMAN et al., 2010). In order to build strong models to detect wide ecosystem impacts from climate change (SCAVIA et al., 2002; KOTTA et al., 2009; SEMENIUK, 2013), we will need replicated experiments on a large latitudinal scale at several Brazilian estuaries.

Broad changes in the structure and functioning of benthic estuarine communities are expected with the projected changes in sea level, temperature and rainfall (NAJJAR et al., 2000; GILLANDERS and KINGSFORD, 2002; MILLIMAN et al., 2008; NICHOLLS and CAZENAVE, 2010; DONEY et al., 2012; BERNARDINO et al., 2015a). Significant changes in rainfall extremes and dry cells have been projected for South America (MARENGO et al., 2010). They include an increase in extreme precipitation events over most of Southeastern South America and Western Amazonia consistent with projected increasing trends in total rainfall. Smaller or no changes in rainfall intensity have been foreseen for Northeast Brazil and Eastern Amazonia, though significant changes are expected in the frequency of consecutive dry days. On estuary- scale, benthic species distribution, diversity and dynamics across salinity gradients may change significantly (ELLIOTT and WHITFIELD, 2011; WHITFIELD et al., 2012). As salinity-community patterns for Brazilian estuaries are understudied in most regions, the loss of species or community changes in these areas will lead to uncertainties about changes in key ecological processes. The benthic fauna associated with vegetated habitats will also be heavily impacted due to habitat loss, which will impact production and trophic processes (LEE, 1998). Sea-level rise effects on Brazilian estuaries are largely uncertain, but will likely lead to loss of mangrove and saltmarsh ecosystems and their services, including carbon sequestration (DUARTE et al., 2005; DONATO et al., 2011). It is clear that most estuarine areas within urban regions will be severely impacted or disappear as vegetated ecosystems will fail to migrate onshore due to coastal development (SHORT and NECKLES, 1999; ALONGI, 2008).

In summary, few ecological and biogeochemical processes mediated by benthic organisms in Brazilian estuaries have been investigated, which precludes reasonable mitigation and conservation strategies if projected changes are confirmed. Mechanisms of benthic production and functional effects on communities in response to natural and anthropogenic disturbance need to be investigated on a multi-scale perspective. It is clear that current and future investigations of estuarine processes need to include the role of benthic communities in sediment biogeochemistry, to address the ecological effects of changes in environment and habitat, and finally to make quantitative predictions of potential environmental, economical and societal changes.

Increase long-term scientific and monitoring efforts

The question of scale in ecology has received much recent attention (LEVIN, 1992; SCHNEIDER, 2001). Studying large temporal scales of ecological processes has been a major challenge for ecologists as well as securing funds for the long-term approaches that are needed to understand these processes. In this context, studies of pattern have become still been more frequent in science, but are strikingly few regarding estuarine ecosystems in Brazil. A number of the ecological benefits provided by estuaries have been independently investigated at a number of sites in Brazil over recent decades (RONDINELLI and BARROS, 2010; PENDLETON et al., 2012; VILAR et al., 2013), but we have no systematic efforts, dedicated funding programs or networks to study Brazilian estuaries. Additionally, the short-term scale (i.e. less than 1-yr) of most studies means that we do not have scientific data on relevant temporal scales to characterize, manage or protect most estuaries and their associated communities in Brazil.

As estuaries are naturally dynamic ecosystems and associated with coastal and riverine hydromorphology, we need to understand changes in their communities and ecological processes on decadal scales in the light of meaningful temporal scales of riverine, marine and climate forces (SCAVIA et al., 2002; ELLIOTT and WHITFIELD, 2011). Long-term studies, with duration of > 2yrs, have an increased power to detect community-wide responses to intra-annual and inter-annual changes in estuarine dynamics. A number of community processes driven by benthic organisms suffer significant changes on time scales longer than a year. For example, population dynamics and benthic annual production rates may vary significantly on annual and decadal scales due to changes in estuarine productivity, temperature, disturbance regimes, catastrophic events and interacting factors (KOTTA et al., 2009; DOLBETH et al., 2011). Although functional indices such as productivity regimes offer advantages in depicting ecosystem-wide responses, large variability in productivity may occur between estuaries due to site-specific differences such as pelagic productivity (CONDIE et al., 2012). Therefore, the multiple mechanisms that lead to changes in production and population dynamics over long-term periods suggest that estuarine ecosystems must be investigated on multiple scales.

The ReBentos Estuaries working group has proposed a study protocol for benthic estuarine communities that meets the above criteria of i) standardisation of methods; ii) working with functional and biodiversity indices, and iii) multiple scales. The protocol has been designed to address projected and observed changes in mean atmospheric temperatures and in yearly rainfall at estuaries in the major climatic regions of Brazil (MARENGO et al., 2010; BERNARDINO et al., 2015b). With scientific hypotheses based on projected changes, we suggested a standard protocol for studying temporal patterns in productivity and diversity of megafaunal and macrofaunal benthic communities. The working group has so far started field work on a total of eight estuaries located in the major regions of Brazil. These estuaries were selected based on their accessibity to various research groups and on existing protected areas (i.e. federal, state or municipal). At each estuary, the working group has started quarterly acquisition of biological and environmental data, with replicated campaigns after dry and wet seasons. We believe that these assessments must be continued, not only to reveal large scale spatial and temporal patterns of benthic estuarine communities, but also to test the hypothesis with long-term data. However, although the ReBentos working group has received a limited startup funding of 3 years, continuous assessments at these estuaries from Northern to Southern Brazil may have to be interrupted.

What international programs can teach us

The International Long-term Ecological Research Network (ILTER) is an example of a global network of scientists engaged in long-term, site based ecological and socioeconomic research, with the mission of understanding global ecosystems and providing potential solutions to current and future global problems, considering the human dimensions of environmental change. The goals of ILTER are to coordinate long-term ecological research in integrated and collaborative networks; to improve comparability of long-term ecological data through simple field and lab protocols; to generate and transmit better scientific information to scientists, policymakers and the public; and to facilitate education of the next generation of long-term scientists. The PELD program (Long-term Ecological Researches), created by the Brazilian National Research Council (CNPq) - Ministry of Science, Technology and Innovation in 1998, was clearly influenced by ILTER. The PELD program is promoting and funding a series of fruitful projects, but none of them have addressed estuarine benthic dynamics on a national scale (TABARELLI et al., 2013).

The U.S. National Environmental Protection Agency has started an Estuary Program (NEP) that initiated several networks with broad objectives including protection and resource governance (SCHNEIDER et al., 2003). Providing up to 5-year funding for creation of management plans for 28 estuaries across the U.S., the NEP program has fostered networks with regional representatives of government, business, citizens, educators and researchers. These networks have been successfully bridging scientific knowledge with policy discussions, and have resulted in the better assessment of impacts on estuaries and their watersheds (SCHNEIDER et al., 2003; MERRIFIELD et al., 2011). Although NEP programs often target regional human impacts on estuaries, the identification of commonalities or dissimilarities in estuarine ecosystems significantly ensures better climate change response and management in these areas (MERRIFIELD et al., 2011). Cimate preparedness and response for estuaries also comes from the US EPA agency specific program named Climate Ready Estuaries (http://water.epa.gov/type/oceb/cre/index.cfm). This program assists the NEP program directly through network actions, and both programs benefit from information produced on scales from local to regional. These joint network efforts are excellent innitiatives for the better practice of estuarine management.

In the European Union, environmental threats to coastal areas have led to political action to protect estuarine and other ecosystems from the effects of human activities (FERREIRA et al., 2011). These policies ultimately led to a Water Strategy Framework Directive (WFD) designed to investigate ecosystem function and to establish guidelines for assessing environmental quality and long-term monitoring of coasts, estuaries and their watersheds (PARLIAMENT, 2000). The WFD has resulted in a number of studies that have developed guidelines to assess all aspects of water and ecosystem quality. As every EU country has been required to follow those directives, national scientific networks across the EU have applied integrated studies regionally to evaluate the ecosystem health of estuaries and their watersheds. In the estuaries and on the coasts of Europe, specific tools for the assessment of ecological status using benthic communities have been created (BORJA et al., 2000) and these have been independently tested in Brazil (MUNIZ et al., 2005; VALENÇA and SANTOS, 2012).

Many other international initiatives across Europe have tested and developed guidelines to investigate benthic estuarine habitats in the long-term with management purposes (QUINTINO et al., 2006; RODRIGUES et al., 2011). As a result, a regulatory directive from the EU Parliament encouraged the creation of scientific and political networks with a view to the assessment of regional ecosystems, the testing of scientific methods and protocols, and coastal management.

These integrated efforts undoubtedly demonstrate that successful programs to protect estuaries call for sound science allied to political and societal engagement. The ReBentos network has started a unique and fruitful network - mainly composed of scientists - that could arouse interest in estuarine management and protection. However, Brazilian efforts to protect estuaries, and most coastal ecosystems, will be largely ineffective if only scientists pursue these objectives (SUNDERLAND et al., 2009). Successful programs to protect Brazilian estuaries from human and climate change impacts will need to be funded by public and private agencies (municipal, state and federal), with the involvement of all stakeholders including scientists, interested parties (e.g. traditional fishermen and industry), private and non-governmental organizations; and result in specific products for management of estuarine ecosystems. Funding for these programs needs to be priorized by federal and state environmental agencies (e.g. CNPq, CAPES, IBAMA; the Ministry of the Environment, the Ministry of Science) which are clearly key players responsible for ecosystem use and conservation. These programs must result in sound scientific practices, with well organized and public data bases (i.e. also funded and maintained by those sources). These programs should be further accompanied and evaluated by progress reports and subjected to rigorous national and international panel evaluations.

Prospects of the studies of the estuaries selected by the ReBentos network

Estuarine benthic communities have been extensively studied across the world and these studies include long-term network initiatives for monitoring. The overall result of changes in species richness, density and biomass related to salinity (MORTIMER et al., 1999; JOSEFSON & HANSEN, 2004), sediment composition (MORRISEY et al., 2003), nutrient input (EDGAR & BARRETT 2002), geomorphology (HIRST, 2004) and oxygen availability (ROSENBERG, 1977; NILSSON & ROSENBERG, 1997) is generally the same. Changes in these abiotic parameters are also related to river and ocean dynamics, natural seasonal climatic changes or anthropogenic impacts, influencing benthic communities (MONTAGNA & KALKE, 1992; FUJII, 2007). Nevertheless, South American estuaries are frequently not included in the search for general ecological models (BARROS et al., 2012), and understanding the patterns and processes which occur along the Brazilian coast would constitute an important contribution to global discussion, due to the extent and diversity of the Brazilian coastline.

The macroscale investigation started by the ReBentos network was the first step towards an integrated approach which takes into account the variety of Brazilian estuaries, their benthic biodiversity and the assessment of the effects of projected climatic change on the goods and services they provide. The effects of large-scale factors on populations and communities are usually underpinned by hierarchical (top-down scale mediated processes) or multiscale (interactions among scales mediated processes) perspectives (HEWITT and THRUSH, 2007; 2009). Both perspectives must take spatial and temporal variation into account. Moving forward, registering, understanding, and reviewing climate change effects on estuarine benthos will require continuous and long-term monitoring. The systematic application of established monitoring protocols will highlight the large-scale and long-term relative importance of environmental factors in influencing spatial and temporal dynamics of benthic richness and abundance, and how their loss can affect estuarine resources and services. The integrated management across spatial and temporal scales and frequent monitoring of estuarine patterns and processes are essential tools for coastal management, since regions under higher pressure from human activities are more suceptible to climatic change impacts. Based on knowledge of the patterns and processes involved in estuarine systems on the long term, further conservation and management decisions can be taken to mitigate impacts. Thus our ability to make better predictions and to provide resource management agencies and policymakers with the best scientific information will depend largely on an increased effort aimed at using integrated research networks over long-term scales.

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